VŠB – Technická univerzita Ostrava
Fakulta strojní
Katedra automatizační techniky a řízení

Řízení a ovládání laboratorního modelu 3D tiskárny
Control of laboratory model 3D Printer

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Projekt RepRap se zabývá vývojem a potenciálem 3D tiskáren jakožto zařízení pro nekomerční využití. Vzhledem k vysokým nákladům běžných 3D tiskáren, nabízí projekt možnost výstavby jednodušších zařízení, které se za cenu ztráty přesnosti a kvality dostávají na přijatelné náklady pro všechny možné uživatele. Projekt je open-source a každý je tímto vítán k přispění svým nápadem celému projektu. Tato práce se zabývá výstavbou tohoto zařízení, pojednává o úskalí, která se můžou objevit při stavbě, a shrnuje jejich nejlepší řešení.

Annotation of bachelor thesis

Jurek, M. Control of laboratory model 3D Printer. Ostrava: Department of control systems and instrumentation, VŠB-TU Ostrava, 2012. 28 pages. Bachelor thesis, supervisor: Škuta, J.

RepRap project deals with the development and potential of 3D printers as a device for non-commercial use. Due to the high cost of conventional 3D printer, project offers the possibility of building a simpler device which by losing accuracy and quality comes at an acceptable cost to all potential users. The project is open-source and everyone is welcome to contribute with their idea within the whole project. This thesis deals with the construction of this machine, discusses the pitfalls that can occur, and summarizes the best solution.

Klíčová slova

RepRap, 3D tiskárna, Prusa-mendel, Arduino

Key Words

RepRap, 3D printer, Prusa-mendel, Arduino

Shortcuts

3D	Three Dimensions
PLA	Polylactic acid
ABS	Anti-lock braking system
uPVC	Unplasticised polyvinyl chloride
UNIMAT	Universal Automat
PLC	Programmable Logic Controller
I/O	Inputs/Outputs
DC	Direct Current
AC	Alternating Current
RAM	Random Access Memory
ROM	Read-Only Memory
EEPROM	Electrically Erasable Programmable Read-Only Memory
CPU	Central Processing Unit
CAD	Computer aided design
RAMPS	RepRap Arduino Mega Pololu Shield
ISP	In-system programming
PSU	Power supply unit
SLS	Selective laser sintering
FDM	Fused deposition modelling
SLA	Stereo lithography
HDPE	High-density polyethylene
PVA	Polyvinyl alcohol
ATX	Advanced Technology extended
Bps	Bits per second
PC	Personal computer
M8	Metric thread (diameter 8)

Content

1. Introduction

I’ve chosen this particular laboratory task to solve, because I’m modeller and I deal with creation of wooden parts for my ships and planes every day. Nowadays 3D printer is more and more interesting topic not only to industry fields but also to public. As the time moving forward, these sophisticated machines are cheaper and cheaper. Driven by idea of having a machine in everyone’s home, which could be able to produce various of objects for everyday needs, RepRap project started. [RepRap Project, 2004],

RepRap is the first project which is aiming to develop self-replicating manufacturing machine. By modification of the structure, material and every individual part, most of the parts used for building this particular 3D printer are actually created by previous 3D printers. This makes the manufacturing of such machines a lot faster, simpler and cheaper. This feature is also bringing possibility of 3D printing to non-corporate customers. By reducing the price and complexity, everyone can build such a device by himself. Every device then can print parts for new one.

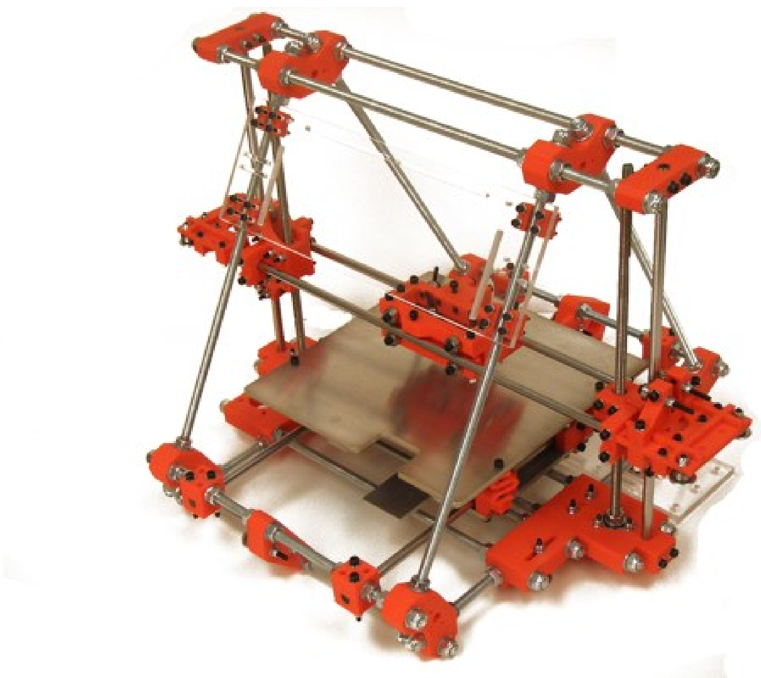

Fig. 1 - RepRap printer [STEMulate Learning 2013]

The idea is to make self-replicating machines freely available for the benefit of everyone. So each printer can easily print parts for new machine as well as interesting objects like hanger, mug, box, spoon or countless other things of everyday need.

RepRap was the initiator of the low-cost 3D printing machines and this project started open-source revolution of 3D-printers. Until now a huge number of people has contributed to RepRap with their own ideas, improvements and changes to 3D printer structure and programming.

The laboratory model should be able to print several of parts possibly needed for other models, for demonstration of automated systems and future improvements. Also different control systems, interfaces or action systems could be tested on this printer and compared to the previous ones.

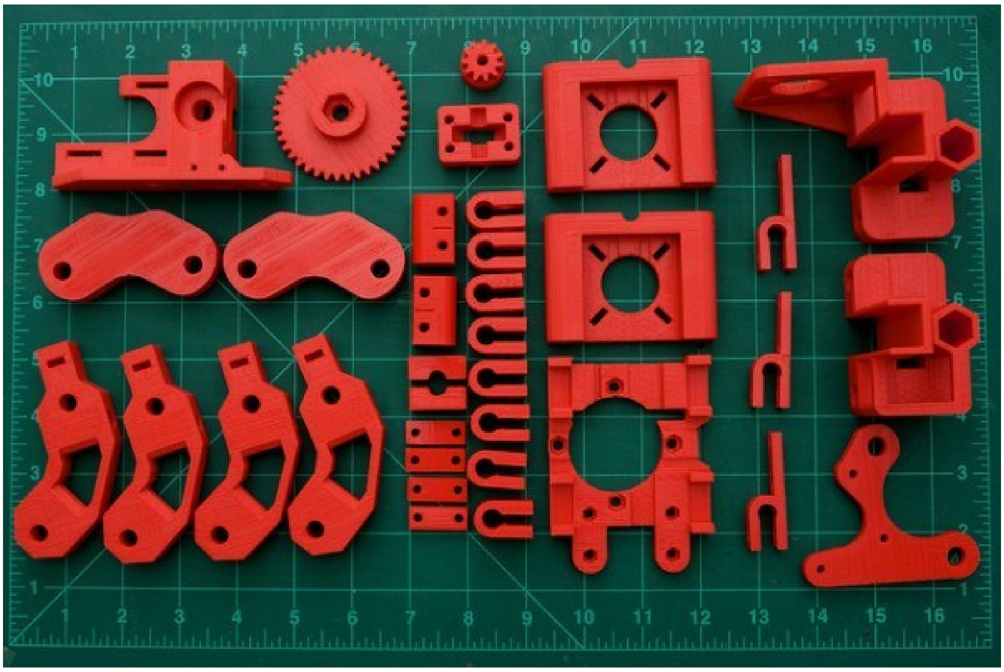

Fig. 2 - Pre-printed parts [All 3D Printers, 2012]

The crucial task for this model is to keep accuracy of 3D printing on sufficient level. Because of reducing the complexity of structure, quality of material and cost, the accuracy of this machine drops down. This also brings quality of printed parts down.

2. Design types of 3D printers

Nowadays a number of different techniques and procedures exist. There are mainly based on additive technology which creates objects through a sequential layering process. They differ in the way layers are deposited to create parts and in the materials that can be used. Most important differences are costs of device, costs of material used, speed, accuracy, colour options and material options. Three main approaches are used in additive 3D printing technology. Methods, which melt or soften material, cure liquid material or cut produced layers, to achieve desired shape.

Two main methods, which melts the material are selective laser sintering (SLS) and fused deposition modelling (FDM). Main principle of SLS is to use high power laser to fuse tiny particles of material e.g. plastic, metal, ceramic or glass, in order to create 3D object. Thin layer of powder is exposed to the laser, which will hit every spot on the layer, where solid object should take a place. After the whole layer is done, machine puts another layer and the whole process repeats according to the input data from CAD model until it's finished. On the other hand fused deposition modelling places the material only to the desired coordinates. It involves printing head which puts the material to individual layers which piles up until solid object created, resolving in 100% use of material. [Z Corporation 2009]

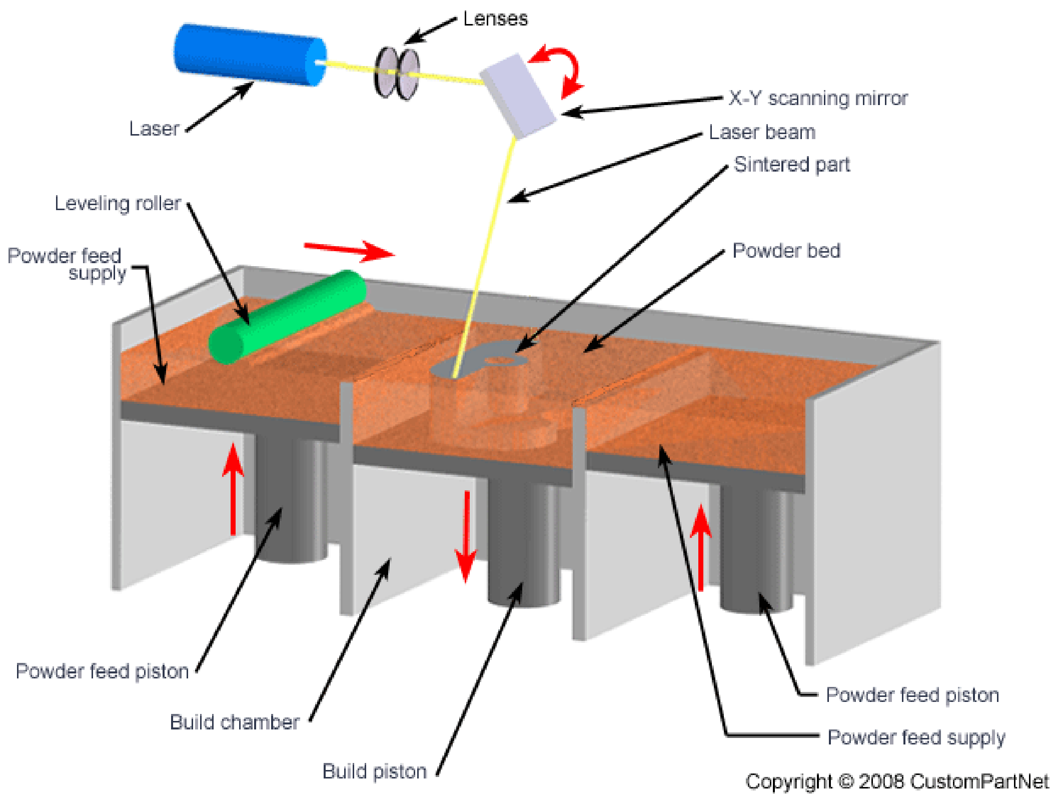

Fig. 3 – Fused deposition modelling principle [Custom part, 2013,B]

Technology which uses liquid form material is called stereo lithography (SLA). This method is based on curing the liquid with UV laser. For every layer, the laser beam traces a cross-section of the printing object on the surface of the liquid material. Exposure to the ultraviolet laser results in curing and solidifying of the pattern traced on the liquid material and joins it to the layer below. [TANG Yanyan, 2005]

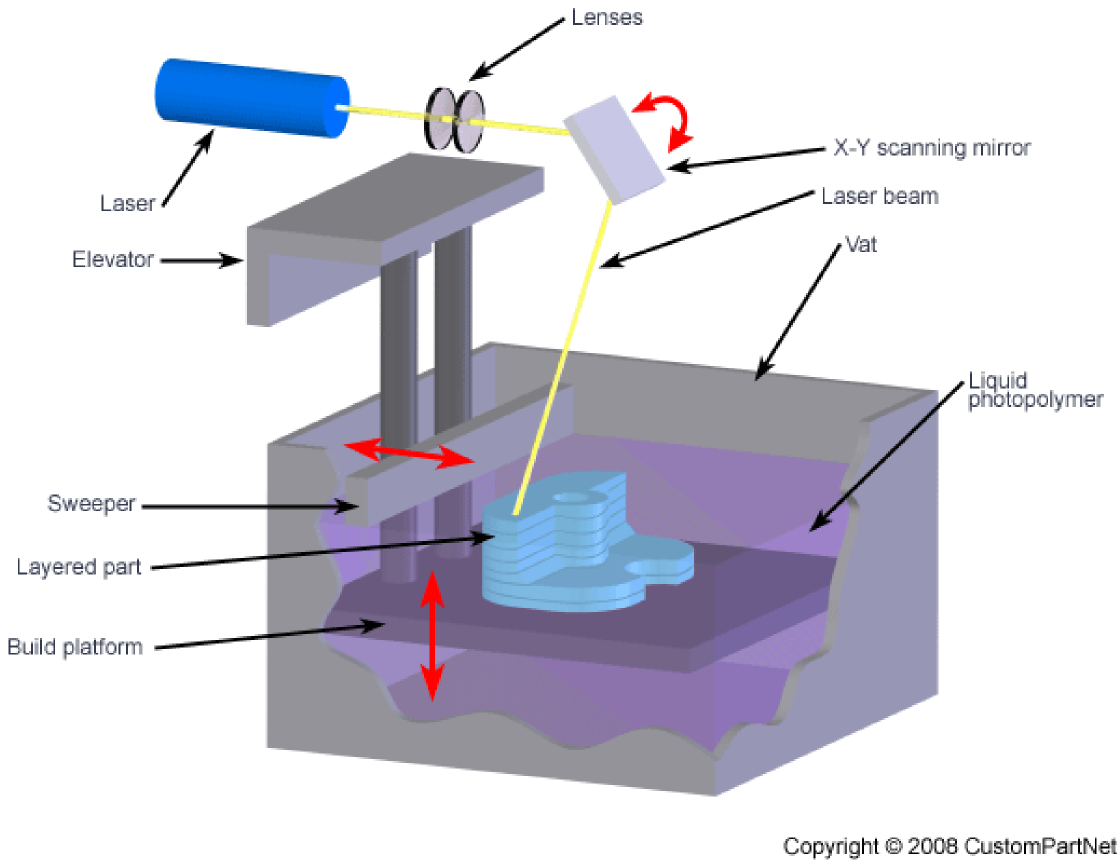

Fig. 4 –Stereo lithography principle [Custom part, 2013,A]

Each method has its own advantages and drawbacks, and some companies consequently offer a choice between powder and polymer for the material from which the object is built. RepRap project is based on fused deposition modelling with low-cost approach.

Printing of objects by this method is very similar to normal printing as we know it today. Instead of ink, there is thermoplastic material used. In RepRap machines printing head is based on heating element, which melts plastic string, coming through brass nozzle. Main board, which holds printing objects is additionally heated in order to slow down the cooling of an objects and ensure better stability and more accurate shapes. Printing head is allocated on the structure made from printed parts, threaded rods and nuts. Its location is determined by 4 stepper motors. The whole construction contains 5 stepper motors in total. One motor for X axis, one for Y axis, two for Z axis and one for loading printing head with plastic string.

The concept of printing is layers-based, where printing head put individual layers on the top of each other. Very important parameter in the 3D printing is density of the printing. Objects can be fully filled with material which provides solid structure but also cause huge consumption of material. The structure can be filled in with thin columns, which support upper layers and create hollow objects with much less material needed.

This method of printing has also its limitations. The machine cannot print movable parts, which touch each other, if not separated after printing manually. Every part of the structure needs support in order not to collapse during the cooling. In this case additional columns can be printed and removed manually after solidification. [RepRap Project, 2004]

RepRap uses thin wires of thermoplastics such as:

ABS (Acrylonitrile butadiene styrene)
Nylon
uPVC (Unplasticised Poly Vinyl Chloride)
PLA (Poly lactic acid)

A lot of individual 3D printer designs exist and this number is rising. The main two groups are professional 3D printers sold by various companies and RepRap project, which involves open source design made by students and other specialists, with pressure to low cost. Since the topic of this thesis is low cost solution for 3D printing and it’s based on RepRap project, only the RepRap solutions are listed below.

Over time, the additional structures and ways of the functionality were developed. The main principle stays but they vary in their disadvantages and advantages. Nowadays we can recognize four main types of RepRap 3D printers.

2.1 RepRap printer Original Mendel

This type of Reprap project printer is second version after Darwin printer. Its improved design makes this type of printer smaller and more portable. It can easily fit on the desk with PC and still, the volume of printing dimensions is almost the same in comparison to the older version. Although the complexity of this particular RepRap design is quite complicated in compare with new ones. Especially the number of pre-printed parts is higher than necessary. This feature makes Original Mendel less popular and more expensive than other types of RepRap printers.

Table 1 – Original Mendel specifications [RepRap Project, 2004]

Size	500 mm (W) x 400 mm (D) x 360 mm (H)
Weight	7.0 kg
Printing Volume	200 mm (W) x 200 mm (D) x 140 mm (H)
Volume of printed parts to replicate	1110 cm3
Positioning precision	0.1 mm

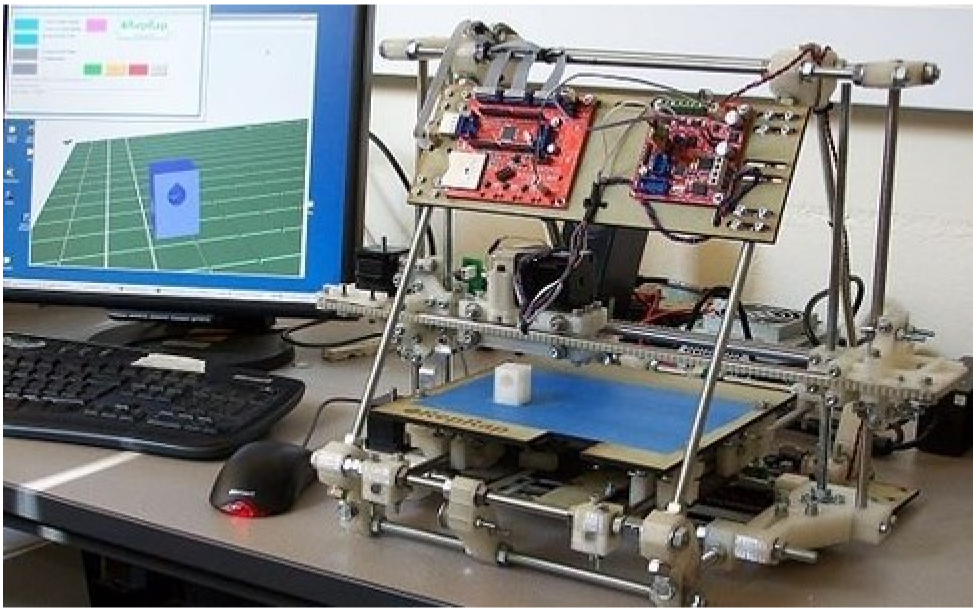

Fig. 5 – 3D printer Original Mendel [RepRap Project, 2004]

2.2 RepRap printer Prusa-Mendel

Prusa Mendel improves on a previous design by making the construction of this device simpler. The main goal of this type is to provide easier to build, modify and repair solution. The predecessor of Prusa-Mendel is Mendel. It was designed by Josef Prusa, young Czech student who lives in Prague. Improvement removed regular bearings, reduced the number and volume of pre-printed parts and adjusted action systems of individual axis.

Table 2 – Prusa-Mendel specifications [Nextdayreprap, 2012]

Size	450 mm (W) x 400 mm (D) x 400 mm (H)
Weight	5.5 kg
Printing volume	200 mm (W) x 200 mm (D) x 100 mm (H)
Volume of printed parts to replicate	172 cm3
Positioning precision	0.1 mm

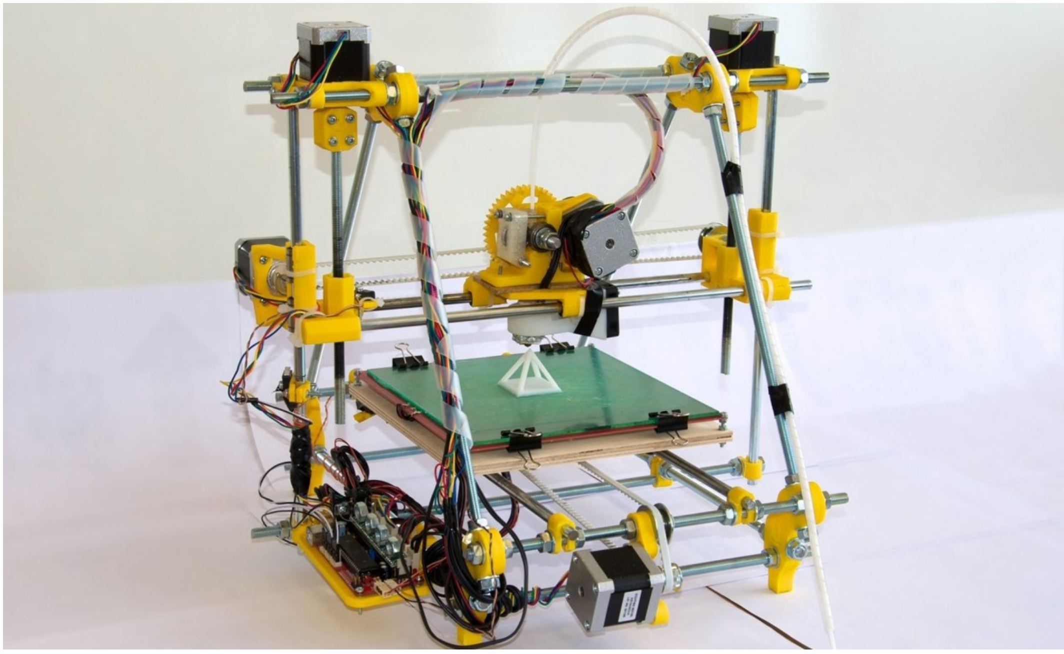

Fig. 6 – 3D printer Prusa-Mendel [Linux Express, 2011],

2.3 RepRap printer Portabee/Wallace

The Portabee was the first conveniently portable 3D printer in the world. It is easily collapsible in a matter of seconds and fits into a laptop bag, making it transportable. Thanks to this feature, you can bring it anywhere with you. It is also very light. The weight of this printer is 2,8 kg. This design solution brings practical use of 3D printing technology a lot closer to everyday use.

Because it's based on Wallace design, it has extremely low part count. From the picture is visible, that it dispose of no supporting rods, while for Prusa-mendel, 13 of them are needed. Only positioning and guiding rods are used in this design.

Table 3 – Portabee specifications [Romscraj, 2013]

Size	360 mm (W) x 300 mm (D) x 96 mm (H)
Weight	2.8 kg
Printing volume	120 mm (W) x 120 mm (D) x 120 mm (H)
Positioning precision	0.1 mm

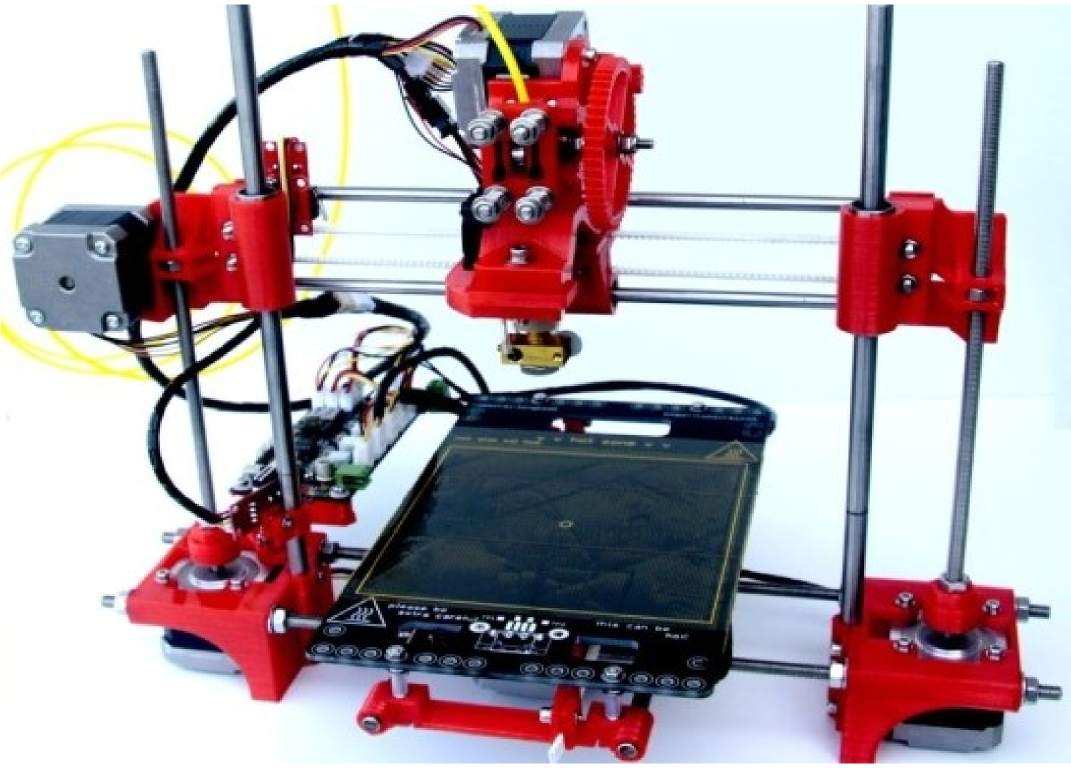

Fig. 7- [Romscraj, 2013]

2.4 RepRap printer MendelMax

This design is based on Prusa-Mendel and it's focused on structural rigidity, rather than use of as much pre-printed parts as possible. Since, threaded rods are not used at all in this design the printer is a lot easier to construct. The body of printer is mainly composed of aluminium profiles and printed parts as joints. Because of improved structural integrity higher positioning speeds can be reached. Device also becomes a much more durable for transportations.

Table 4 –MendelMax specifications [Maker's Tool Works, 2012]

Size	450 mm (W) x 340 mm (D) x 460 mm (H)
Weight	16 kg
Printing volume	245 mm (W) x 315 mm (D) x 225 mm (H)
Positioning precision	0.1 mm

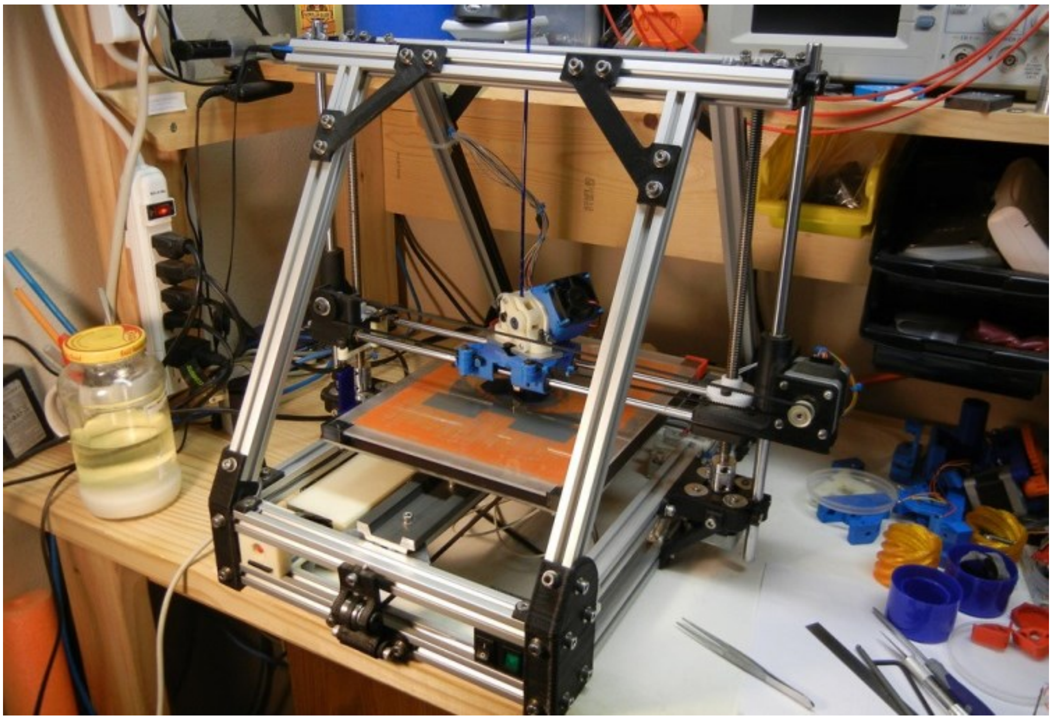

Fig. 8 – 3D printer MedelMax[RepRap Project, 2004]

2.5 3D printer MakerBot

MakerBot Industries is company located in Brooklyn, New York. It was founded in January 2009 by Adam Mayer, Bre Pettis and Zach Smith. Main products are 3D printers, which builds on the early stage of RepRap Project. The company's preserved strategy - the idea of low-cost 3D printers provided anyone for affordable price.

In contrast to the open source RepRap project, MakerBot development is not focused on the idea of self-replication, rather than pure manufacturing of more precise objects for everyday use. MakerBot printers are designed to be composed by anyone with basic technical skills. Delivered assembly kits are very simple and involve only minor soldering. Since the technology used for MakerBot is the same is for RepRap same materials are needed. Nowadays MakerBot industries provide their customers with acrylonitrile butadiene styrene (ABS), high-density polyethylene (HDPE), polylactic acid (PLA), and polyvinyl alcohol (PVA). [MakerBot, 2010]

Table 5 – MakerBot specifications [MakerBot, 2010]

Size	320 mm (W) x 467 mm (D) x 381 mm (H)
Weight	11,5 kg
Printing volume	225 mm (W) x 145 mm (D) x 150 mm (H)
Positioning precision	0.0025 mm (Z axis); 0.011(X,Y axis)

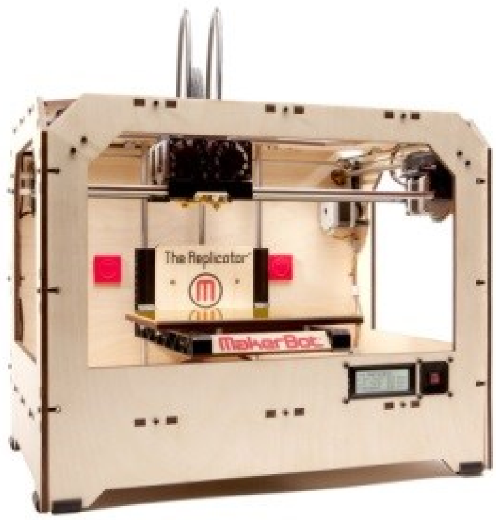

Fig. 9- MakerBot printer [MakerBor, 2010]

With feature of low cost and easy to build the RepRap is one of the most used and known solution for 3D printing across the world which shows the potential of this project and its usefulness. The statistics which has been created about 3D printing shows the RepRap project as the most widespread manufacturer. Another largest representation belongs to Objet and MakerBot.

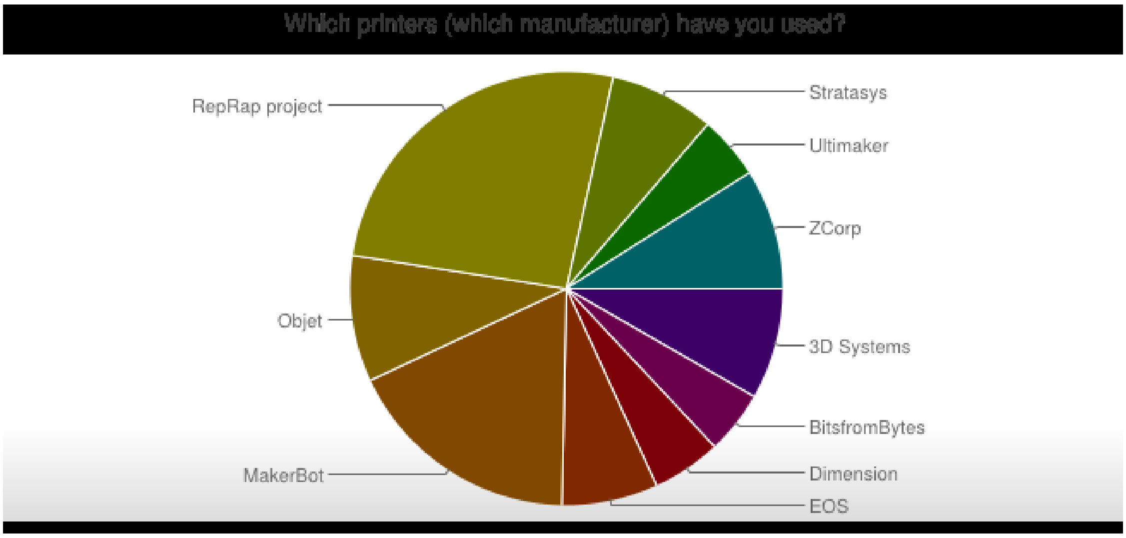

Fig. 10 - Chart of 3D printing solutions [P2P Production 2013]

3. Possible modification

Since this thesis deals with low-cost approach, the main focus of possible modifications is to constructional options. As mentioned in previous chapters, the principle of self-replicating machine is to be able to print as many parts as possible, needed for further construction of next devices. However some parts, which were suggested by the RepRap project, can be easily replaced by much cheaper and simpler solution.

The main idea of self-replicating device will remain valid, until pre-printed parts are rather just adjusting or removing, than replacing by non-printed options. In order to preserve this idea, only non-printed and unnecessary parts were questioned from possible modification or removing.

3.1 End stops mounting

End stop is system, which is mounted at the very end of every axis and it ensures safety for printer in case of collisions. These systems are providing with switch-off in case, printing head hits the end of individual axis.

There are few possibilities how to build this system. For detecting the collision of printer head with end of each axis, optical, mechanical contact or mechanical contact-less switches can be used.

Mechanical switches are less complicated to implement and cheaper than optical endstops because they do not require a circuit board and only use 2 wires for connecting the switch. Pull up and down resistors can be put close to the main board. Contact-less magnetic switches are called reed switches. They are proximity switches that close (or switch over) if a magnet comes close enough (usually 1mm or less) and open if the magnet moves away. Reed switches are used as sensors in home alarm systems to detect open windows and doors.

Typically mechanical contact switches are used. This option is mainly represented by micro switches. A miniature snap-action switch, also trademarked and frequently known as a micro switch, is an electric switch that is actuated by very little physical force, through the use of a tipping-point mechanism, sometimes called an "over-centre" mechanism. Switching happens reliably at specific and repeatable positions of the actuator, which is not necessarily true of other mechanisms. They are very common due to their low cost and durability, greater than 1 million cycles and up to 10 million cycles for heavy duty models. This durability is a natural consequence of the design. [HONEYWELL 2009]

Mounting of microswitches is ensured by printed part by RepRap project. This approach raises part count for printing, which results in larger material consumption and higher price for construction of new model. For model, described by this thesis, simple zip tie is used. This modification lowers the price of printer and makes mounting of microswitch faster, easier and more accurate. The only disadvantage is that this option is based on non-disassemble connection. Every disassembling will result in permanent damage to the zip tie and requirement for new one. However, there is only low expectation for needs of reconnection for microswitches.

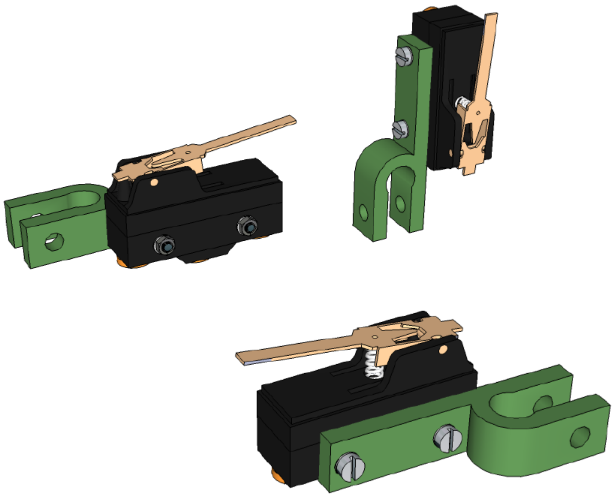

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Fig. 11 – RepRap endstop holders [Hodgson, 2012]

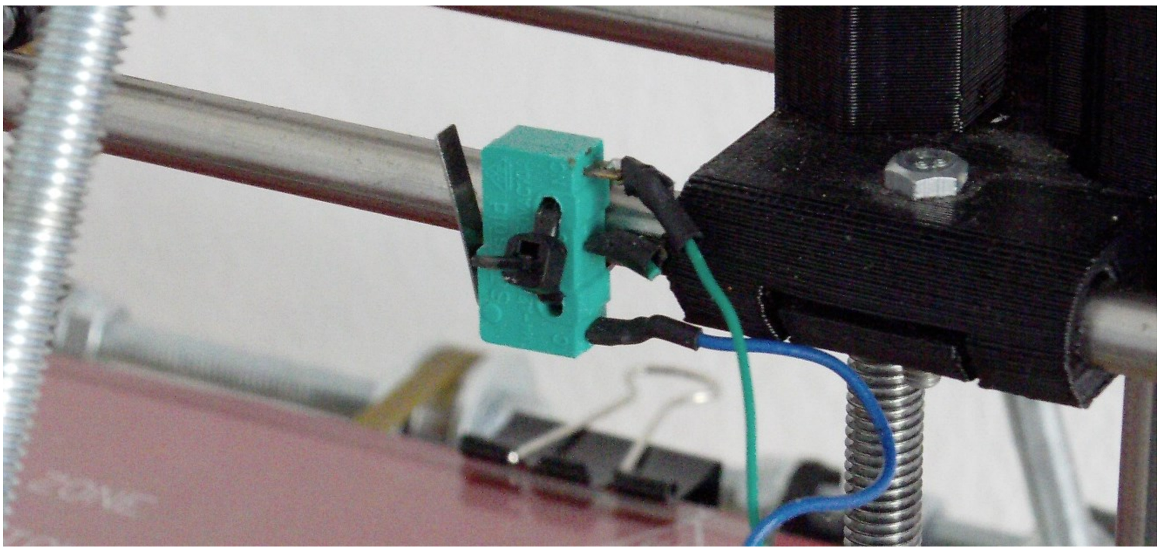

Fig. 12 - Alternative endstop holder system

3.2 Shaft coupler of Z axis motors

While for X and Y axis, pulley and timing belt system is used for propulsion, Z axis is actuated by threaded rods and nuts. In order to rotate threaded rods, connection to the shaft of the motor is required. For transferring the rotary motion from drive shaft to the driven shaft, shaft couplers are usually used. In this particular laboratory model solution, different design of coupler is proposed.

In design of the coupler, rubber hose is used. Since only minor torque is produced by NEMA stepper motors, this coupler is able to precisely transmit the rotary motion. Rubber hose, with inner diameter of 5mm was chosen. For sufficient grip strength durable zip ties causing inner diameter to shrink to 4mm are implemented. For fastening the grip of the hose, additional heating can be used on the hose, for thermal expansion of material, before implementing. On the hole for threaded rods, tap and die was used for carving a M8 thread inside the hose. By this, strong connection to the threaded rods is achieved.

This coupler provides safer approach for the printer. The connection is just strong enough to transmit the motion without downtimes but weak enough for causing serious damage to the printer. This feature supports endstop system and provides more protection for the printing head. In case of collision or misalignments of axis, motor starts slipping in the hose. By this action, motion of Z axis is stopped, preventing from damage causing.

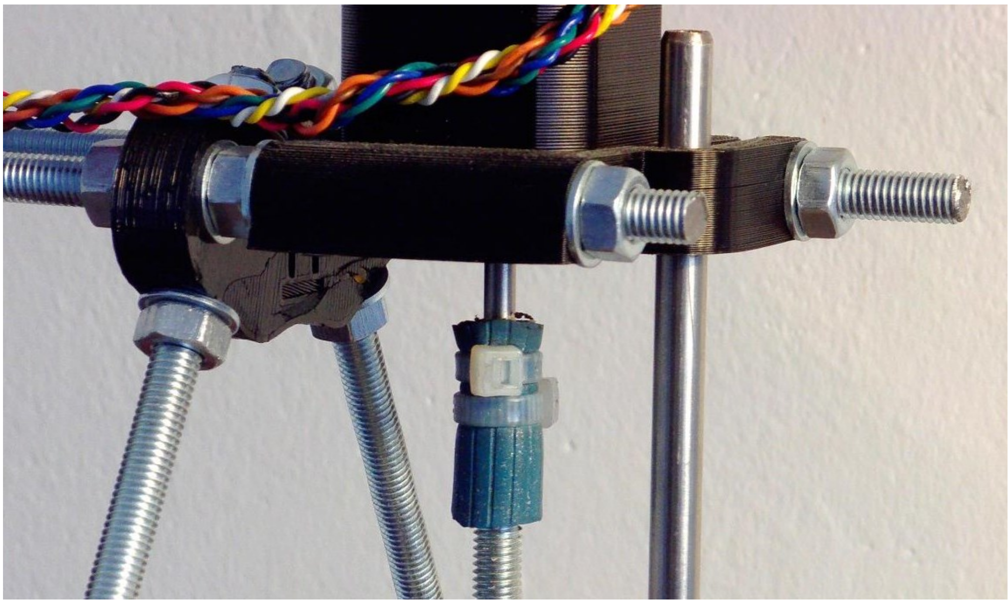

Fig. 13 - Modification of coupler

3.3 Guiding inserts

Design of RepRap printers, involves smooth guiding rods for axis motion systems. To ensure precise sliding of printer head and Z axis system, special linear bearings are used. Since considerable amount of printers are made by low-cost approach, significant problems can appear during construction. Shaft tolerance between bearings and guiding rods is one of the typical problems.

On this model solid inserts from plastic material are tested. Solid inserts dispose of sufficient accuracy and additional changes for individual inserts can be done by simple hand tools. For example: adjusting the inner diameter with file. Unfortunately, by implementing of solid inserts, friction on the rods is increased. By sufficient lubrication system should be fully operational.

The main advantage is reducing the costs. Since a minimum of 8 bearings are needed for implementation, it becomes considerable item in billing list. One LM8UU linear bearing costs approximately 3.85€. By this total price of 30.8€ is achieved. Since with possibility to use lathe, price of solid inserts depends only on material, all inserts can be created for less than 1€. Because total price of model, described by this thesis is around 600€, price for LM8UU linear bearings, play an important role. [Wiltex, 2012]

Fig. 14 - Modified inserts

3.4 Interconnection with PC

Control of RepRap printers is accomplished by so called G-code. It's a set of codes, which carry commands to printer (turn on heater, move X axis motor etc.). For establishing connection, G-code interpreter software has to be installed to both devices. For PC G-code interpreter is called Host software and for the control board of the printer it's called firmware.

The very first step is connecting the control board to PC. In this case it is Arduino board. Since this company has really good customer support, it is quite easy to install proper driver and set up the right COM port for the board. After setting up the port, bitrate of this connecting has to be set to 115200 bps.

After the connection is established, the Arduino development software has to be installed. This is also not a problem since there is quite clear step by step guide on the Arduino web page. Arduino development software is used for creating and uploading programs into Arduino memory. Because of Arduino's automatic boot loader, after every press of reset button on the Arduino board, the board is checking for incoming program from PC. That means before every upload the reset button has to be pressed. Once the program is successfully uploaded to the Arduino's memory, the microchip starts executing the program logic, until it's disconnected from power supply. Once reconnected, it will start the program again.

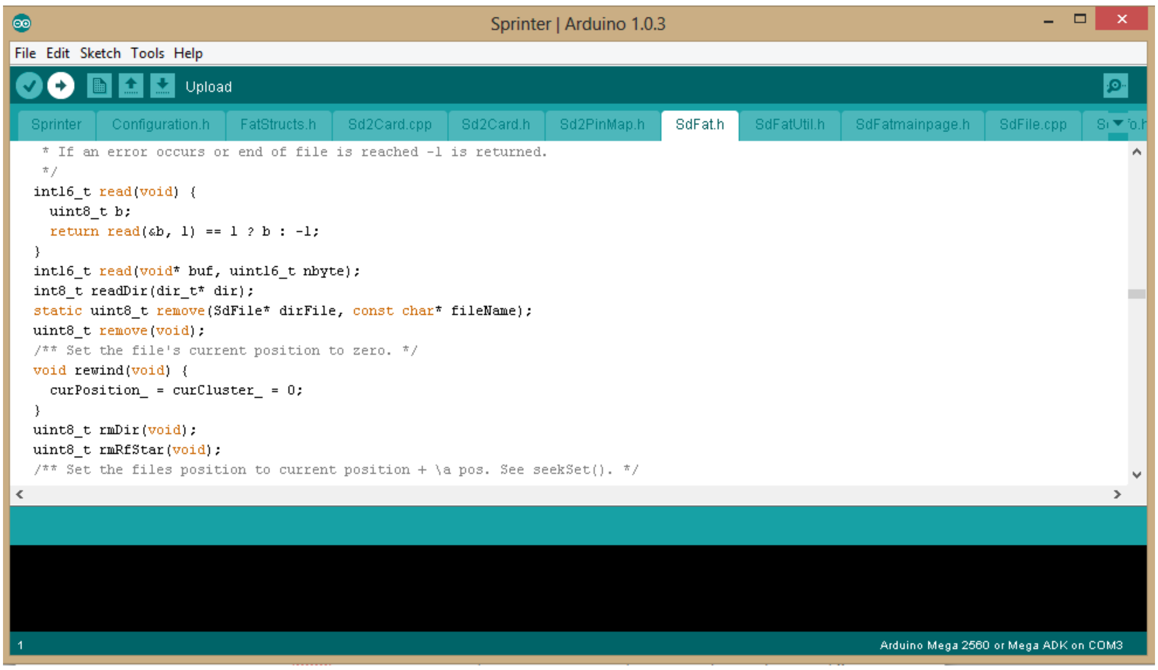

Fig. 15 – Control firmware in Arduino environment

There are four most common firmware versions for controlling the board:

Sprinter- Authors are Kliment, Caru, Tonok and Tesla893. This firmware is active as of February 2012. It is compatible with RAMPS, Sanguinololu, Teensylu, Ultimaker's Electronics version 1.0-1.5 and Generation_6_Electronics control boards for RepRap designs.

Teacup– Authors are Triffid_hunter, Traumflug and Jakepoz. It is active since December 2012. Compatibility is ensured for Generation 3, Pololu Electronics, RAMPS, Generation 7 Electronics, Sanguinololu and Teensy control boards for RepRap designs.

Marlin–Authors are Erik van der Zalm and Bernhard Kubicek. Active as November 2011. Compatibility is with RAMPS, Sanguinololu, Ultimaker's Electronics version 1.0-1.5 and Generation_6_Electronics control boards for RepRap designs.

Sjfw- Author of this firmware is ScribbleJ. It is active in use from August 2011. This firmware is compatible with Generation_4_Electronics, RAMPS 1.2/1.3 and Sanguinololu control boards for RepRap designs. [RepRap Project 2004]

After firmware is successfully upload to the control board through uploading possibility of Arduino development software, installation of Host software on PC is next. Again there are more possibilities for Host software solution. Nowadays the most update and popular one is called Printrun. It is a set of G-code sending applications. It consists of Printcore (G-code sending application), Pronsole (command line G-code sender) and Pronterface (G-code sender with user interface). It is used together with Skeinforge software, which is a tool capable of converting 3D objects to G-code instructions. Once important prerequisites for these two programs are installed on the PC, Host software will be operational. Among essential software for Printrun and Skeinforge belongs:

Python (Printrun’s and skeinforge’s programming language)

PY serial (library which provides support for serial connections)

Pyreadline (Important extension for Python and international characters recognition)

Pyglet (which software library used for developing games and animations using python) [Jakub Šerých 2007]

The most important step, which affects accuracy of printing, is Skeinforge software setting. Also the fineness of the print quality depends on the nozzle size, the speed of the print and the layer height. The basic parameters for setup are:

Layer Height (Layer thickness): This feature controls the thickness of each layer, how 'fine' the object is printed or resolution. Mainly the accuracy of Z axis is modified by this setting.

Extrusion Width: This attribute determines the width of the extrusion, and controls placement of lines of plastic. Lower width of extrusion ensures more detailed printing, but also extends the time needed for creating of model.

Extrusion Rate is actually separated into 3 separate settings:

Edge Width over Height

Infill Width over Thickness

Extrusion Diameter over Thickness

Feed Rate (Head Speed): This is how fast the build platform moves, in millimetres per second. The 'standard' profiles are usually around 30mm/second

Flow Rate This is the rate at which material passes through the nozzle. This feature adjusts the amount of material extruded in time. Material is delivered to the nozzle by special feeding system, driven by fifth NEMA stepper motor. [Dave Duran 2010]

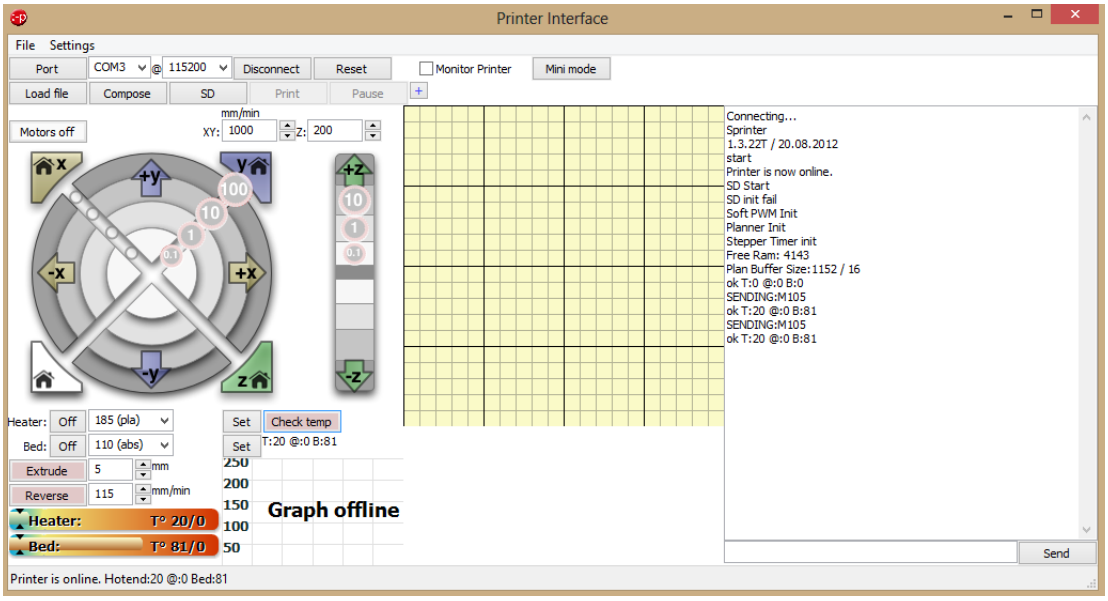

Fig. 16 – Software interface Printrun

4. Implementation documentation

The construction of the model is quite complex but with all needed information and materials printer can be up and running in one week.

We can divide the whole implementation process into six steps:

1. Choice of desired design
2. Raising all parts required
3. Mechanical construction of model
4. Electrical implementation
5. PC connection establishing
6. Calibration
7. Printing procedure

4.1 Choice of desired design

There are a lot of various designs with their advantages and disadvantages. The most common types of RepRap project are listed in chapter 2. Decision should be based on requirements for printer. One of the most important properties of every 3D printer are purchase price, the complexity, size of printing area, colours possibilities, operating costs and the precision of the printed object. [RepRap Project, 2004]

Table 6 – Various designs specifications [RepRap Project, 2004]

Model	Size [mm]	Weight [kg]	Volume [mm]	Precision [mm]	Price [€]
Original Mendel	500x400x360	7	200x200x140	0.1(Z); 0.1(XY)	650
Prusa-Mendel	450x400x400	5,5	200x200x100	0.1(Z); 0.1(XY)	600
Portabee	360x300x96	2,8	120x120x120	0.1(Z); 0.1(XY)	400
MendelMax	450x340x460	16	245x315x225	0.1(Z); 0.1(XY)	1150
MakerBot	320x467x381	16	225x145x150	0.0025(Z); 0.011(XY)	1360

4.2 Inventory preparation

This step is the most variable of all six steps. The total price of a printer is directly derived from choices of vendors and approaches. Construction of RepRap model includes so called vitamins, electronics and printed parts. Printed parts are mostly joints and wheels, which creates the structure of model. These parts are most often made by some already working RepRap printer. Specification and dimensions of these parts are available at RepRap wiki community and stored online freely for every internet user. All other mechanical parts are called vitamins. Threaded rods, guiding rods, nuts, screws and washers belong to that group as an example. After mechanical structure is completed, electronic parts follow. Motors, wires, control boards, end-stops, power supply, thermistors, heating bed, heater and other important parts have to be obtained. There are three main possibilities how to deal with this step.

Special building kits can be bought from different vendors, in which all necessary parts are included. This option is the most expensive one, but since all parts are provided from one vendor, compatibility is ensured. Various kit sizes are available at online stores. Other than price, the only disadvantage of this approach is limited construction adjustments. Complete list of needed parts is listed in attachments. (Table 8)

Fig. 17- inventory of all parts [Lmnts, 2011],

Next option is to buy individual parts from individual vendors. Some savings can be achieved by this method. Printed parts are mainly bought or obtained from other owners of 3D printers. Other components can be bought from specialized stores for the reasonable price. However, disadvantage of this method is that compatibility of parts, obtained by this procedure is not ensured. The probability of running into some problems, where additional adjustments are required is quite high. On the other hand a lot of improvements can be made by choosing more suitable parts or systems.

The last variation is to build 3D printer as much by one's own as possible. This is possible, because RepRap project is open-source and design specifications to all parts are provided on the internet. With this approach, control boards, printing head, heating bed and a lot of other parts are possible to build, which results in vast savings. Some design specifications of crucial and most expensive parts are listed in attachments.

4.3 Mechanical construction of model

Construction of model's structure is quite simple and fast. Prerequisites for these steps are all mechanical parts obtained and basic mechanical engineering tools. Since RepRap is open-source a lot of handy tips and procedures can be found on the internet. The construction of main body takes about 25 hours.

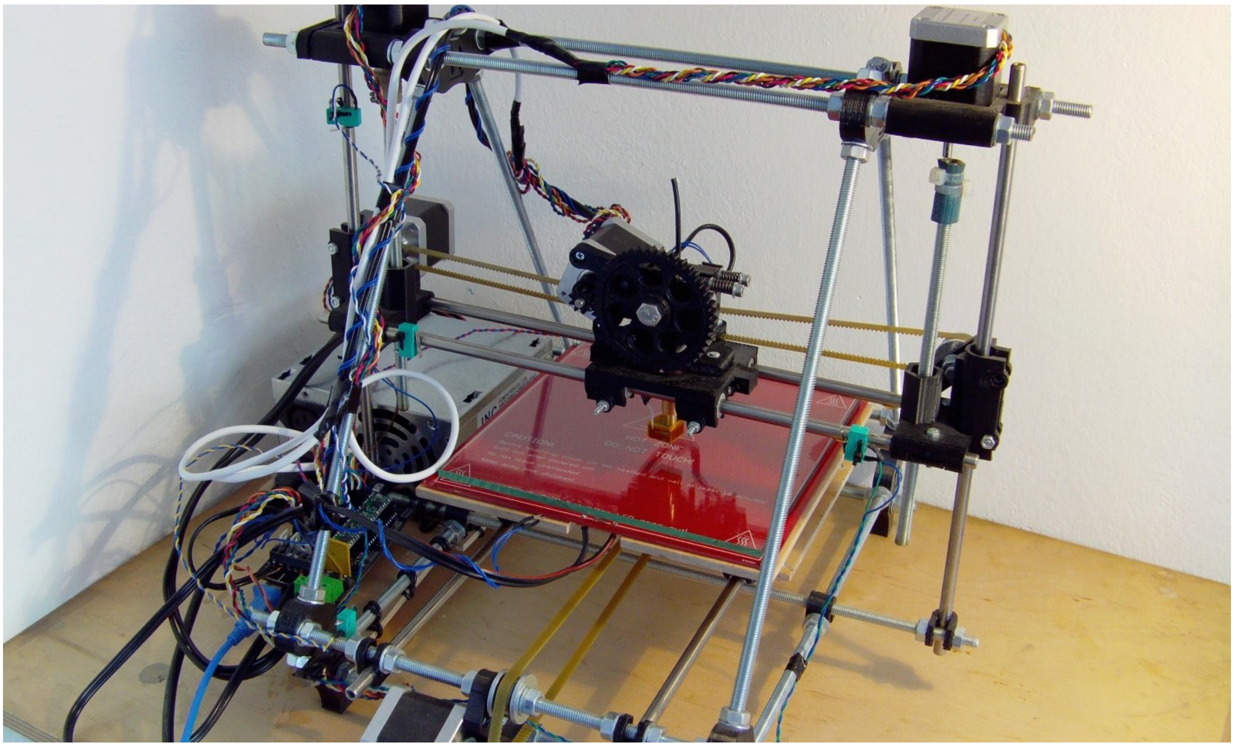

Fig. 18 - Body of RepRap 3D printer

First step is dividing of threaded rods to desired dimensions. The main body consists of two triangle conjunctions which are joined by six threaded rods together. By this systems low-cost and stability of structure is ensured. X axis is based on two smooth guiding rods and timing belt positioning. The timing belt is moving with printing head along guiding rods. It's powered by one stepper motor with pulley. Y axis is based on the same principle, but the whole printing table is moved by this system. Z axis is the only axis, which by two stepper motors is driven. This is, because printing head and the whole X axis positioning system has to be carried along the Z axis. It consists of two smooth guiding rods and two threaded rods. Thanks to the threaded rods positioning system, precision of Z axis is much higher, than precision of X and Y axis.

After main body is completed, positioning systems are ready for implementing. In X and Y axis, timing belt, motors and pulleys has to be placed and tighten. In Z axis, both motors have to be joined to threaded rods.

The printing head is creating objects on the printing table. This table is moved by Y axis positioning system along Y axis guiding rods. To prevent any damages and ensure flatness this table is springy by four ball pen springs. Also heat bed and protective glass is carried by it.

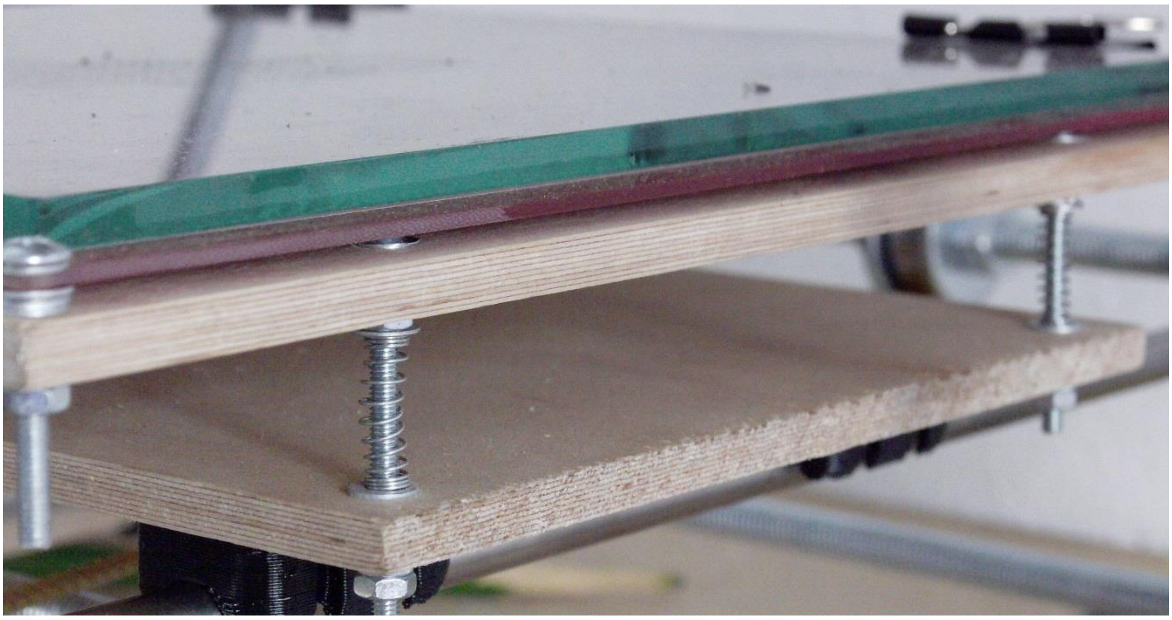

Fig. 19 - Springy printing plate

4.4 Electrical implementation

Electrical equipment of standard RepRap design includes hot-end of printing head, stepper motors, control board, power system board, thermistors, end-stops, power supply, wires, heat bed and controlling diodes.

The first important part is the power supply. Most commonly Power supply units (PSUs) from PCs are used. Minimum of 16 Amps on +12V junction is required for powering the printer. At least 20 Amps is recommended. Although a lot of other options are possible, as far as it's able to provide minimum of 11+5A on 12V, DC. For adjusting PSU for RepRap system few modifications are required. First of all the green wire from ATX or ATX 12V junction has to be connected to the ground in order to start up the PSU. Then all +12V and some ground wires have to be used and connected to the power system board. For PSUs with two +12V branches is advised to keep those branches separate.

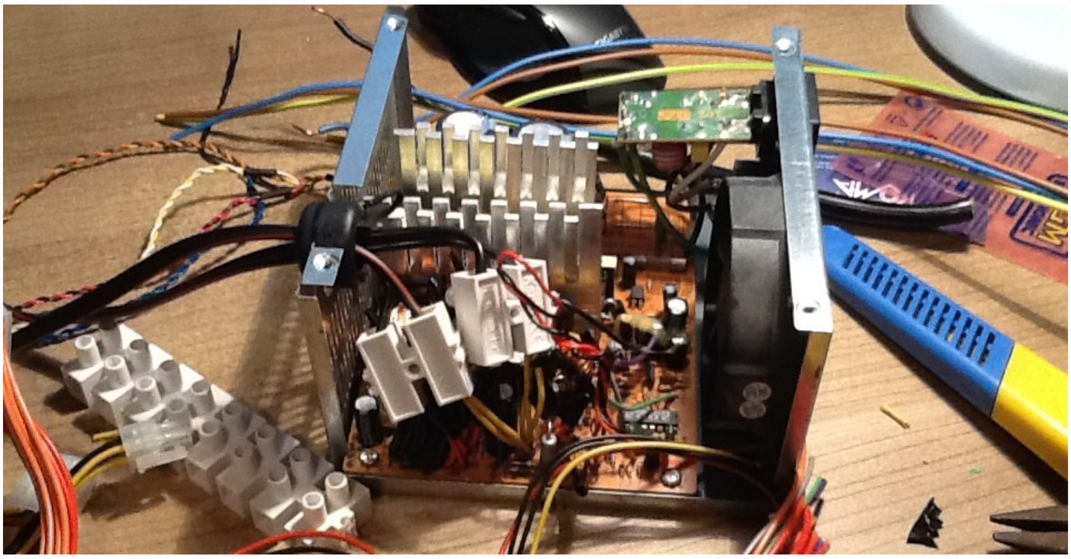

Fig. 20 - Adjusted ATX power supply

The standard RepRap system is driven by five stepper motors. Four of them are used for positioning of printing head and the last one is filling the printing head with filament by driving the feeding system. The RepRap projects are based on NEMA 17 stepper motors. Those types of motors have proven to be most suitable for positioning and structure. Although these are standardized, they are available with four, six and rarely even eight wire connection. Most of power system boards of RepRap project are designed for 4-wires motors, nevertheless with special adjustments, it is possible to use all of them, because the inside structure is the same. [RepRap Project 2004]

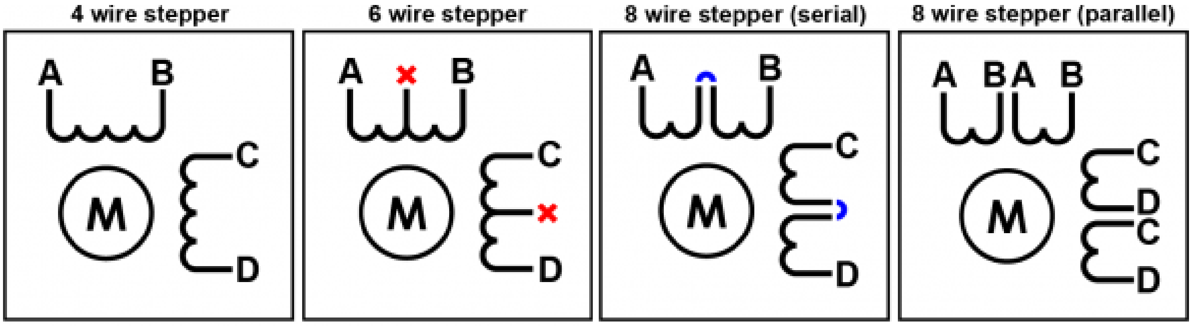

Fig. 21 - Stepper motor wiring

Next important element is control system. Again there are various possibilities for RepRap printers. In this thesis, the RAMPS 1.4 control system designed by RepRap community is chosen. RepRap Arduino Mega Pololu Shield, or RAMPS for short. It is designed to fit the entire electronics needed for a RepRap in one small package for low cost. RAMPS interfaces an Arduino Mega with the powerful Arduino MEGA platform and has plenty room for expansion. The modular design includes plug in stepper drivers and extruder control electronics on an Arduino MEGA shield for easy service, part replacement, upgrade-ability and expansion. Additionally a number of Arduino expansion boards can be added to the system as long as the main RAMPS board is kept to the top of the stack. The control board schematics are enclosed in the attachments.

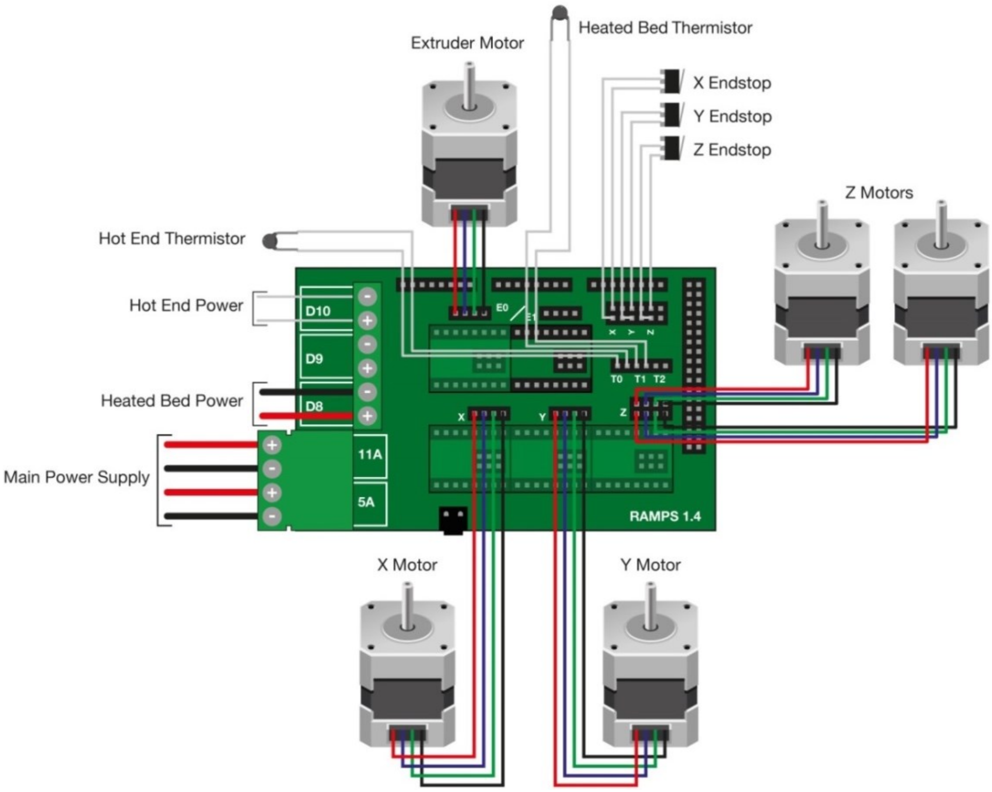

Fig. 22 - Wiring diagram of RAMPS [Nextdayreprap, 2012]

Since 3D printer is using 5 stepper motors, RAMPS control system includes 5 Pololu shield controllers. The type of Pololu electronics is A4988, which has outputs for four wired motors. To set up the correct current for NEMA 17 motors, small trimmer is placed on the driver board. By adjusting the trimmer, voltage on the driver's measuring point is changed. The desired current is calculated from this equation: [Pololu Corporation, 2001]

$$I = \frac{V_{REF}}{0.4}; [A]$$ ***(Pololu Corporation, 2001)***

For NEMA 17 motors voltage 0,4V is recommended. Driver board is connected to the RAMPS 1.4 board and it sends pulses to stepper motors in order to produce desired motion.

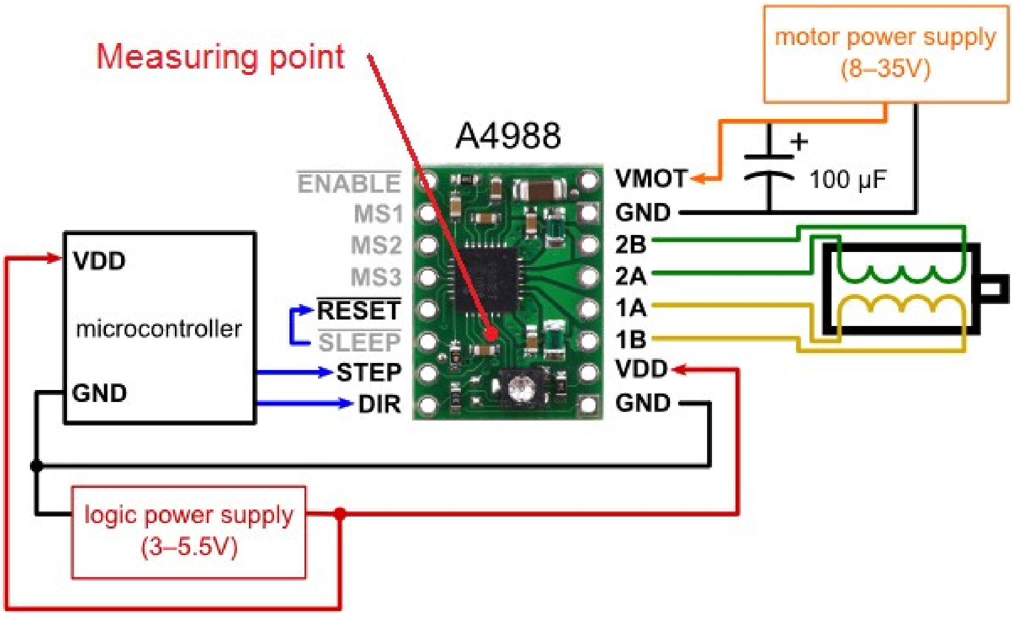

Fig. 23- Pololu driver board wiring diagram [Pololu Corporation, 2001]

Another important part of the RAMPS control system is Arduino board. Arduino Mega 2560 is development board based on ATmega2560 microchip. It's 8-bit microchip, which belongs to AVR family. Program instructions are stored in FLASH memory, which is rewritable and retains data even without power supply. Every command which is proceeding has to be stored on this FLASH memory. AVR microchips are not able to execute instructions from external data storage. Programming of AVR microchips is mostly performed through ISP. Arduino has also USB connection possibility. Common programming languages in these microchips are C, C++, Ada, Basic, Forth, Java, Pascal or Python.

Fig. 24 - Arduino Megaboard

Table 7 - Arduino Mega2560 specifications [GM Electronics 2013]

Microcontroller	ATmega2560
Operating voltage	5V
Input voltage	7-12V
Max. input voltage	6-20V
I/O pins	54 (of which 15 provide PWM output)
Analogue inputs	16
DC current on pin	40 mA
Flash memory	256 KB (8 KB used for boot loader)
SRAM	8 KB
EEPROM	4 KB
Clock Speed	16 MHz

4.5 Calibration

After mechanical body, electronics and software is installed on the printer, everything needs to be properly calibrated. Since all printers are different, every printer has its own setting and features which needs to be kept in mind. For precise positioning the whole firmware has to be adjusted to fit the individual device. Once the mechanical body is aligned, process of calibration may begin.

The very first procedure is calibration of stepper motors in all axis. Since multiple motors are available on the market, the amount of steps needed for 1mm move, may vary. This constant has to be adjusted in firmware, installed on the control board. This entry is called exis_steps_per_unit. The calibration itself is not complicated. The idea is to send control command to the printer, to move each axis for example 50mm. When motors stops, the real distance of relocation for every axis is measured and compared to the expected distance. The new value is calculated by simple proportion. To perform this process two times to reach desired precision of printing is advised.

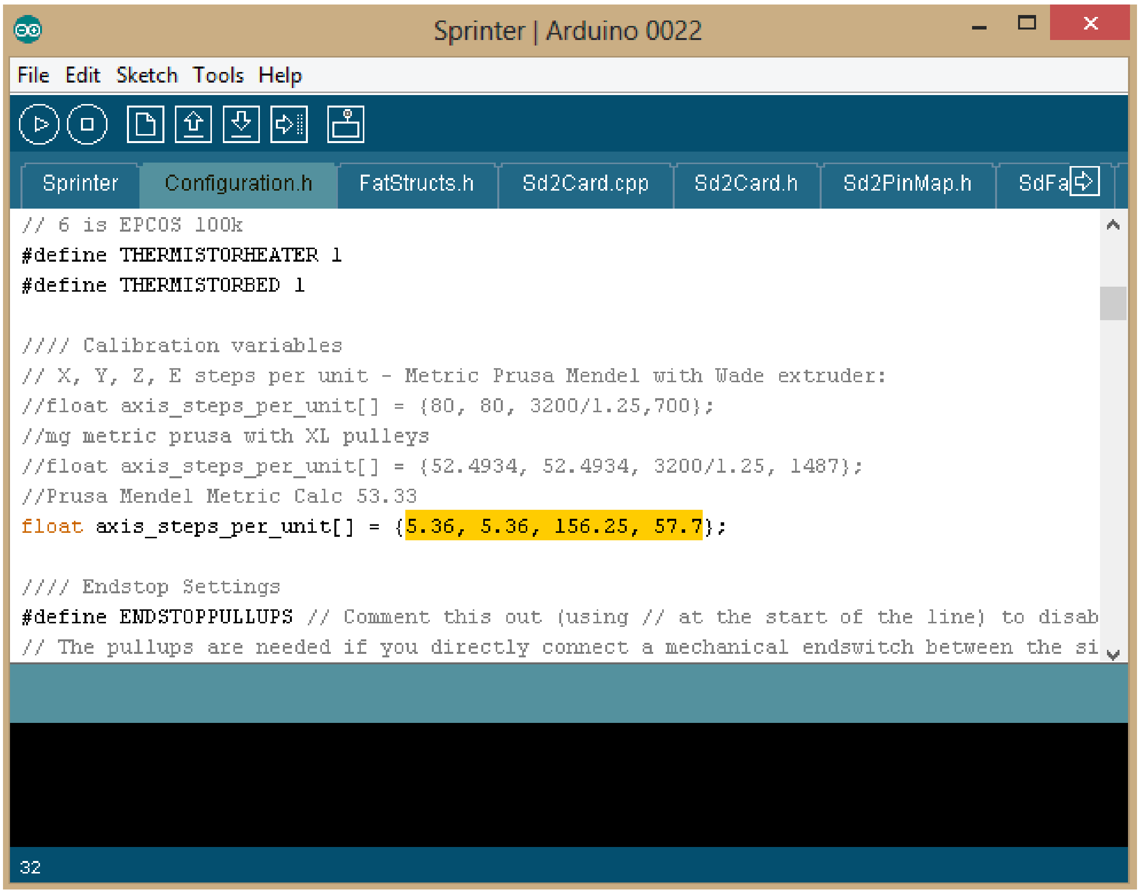

Fig. 25 - Configuration of Sprinter firmware

Next calibrating process is heat bed levelling. The printing surface needs to be horizontally calibrated in order to ensure the same high of printed layers in every corner on the heat bed. To achieve this state, printer head is placed very close to the printing surface and it's moved around to measure distances between printing head and head bed in every corner. Right after springy bolts are adjusted to reach optimal position of printing surface.

Multiple input constants are essential for smooth printing. Information about nozzle diameter, material of filament, diameter of filament, temperatures for both heat bed and extruder head and characteristics of thermistors are the most crucial. They need to be set in Pronterface software and during the 3D model to G-codes list conversion.

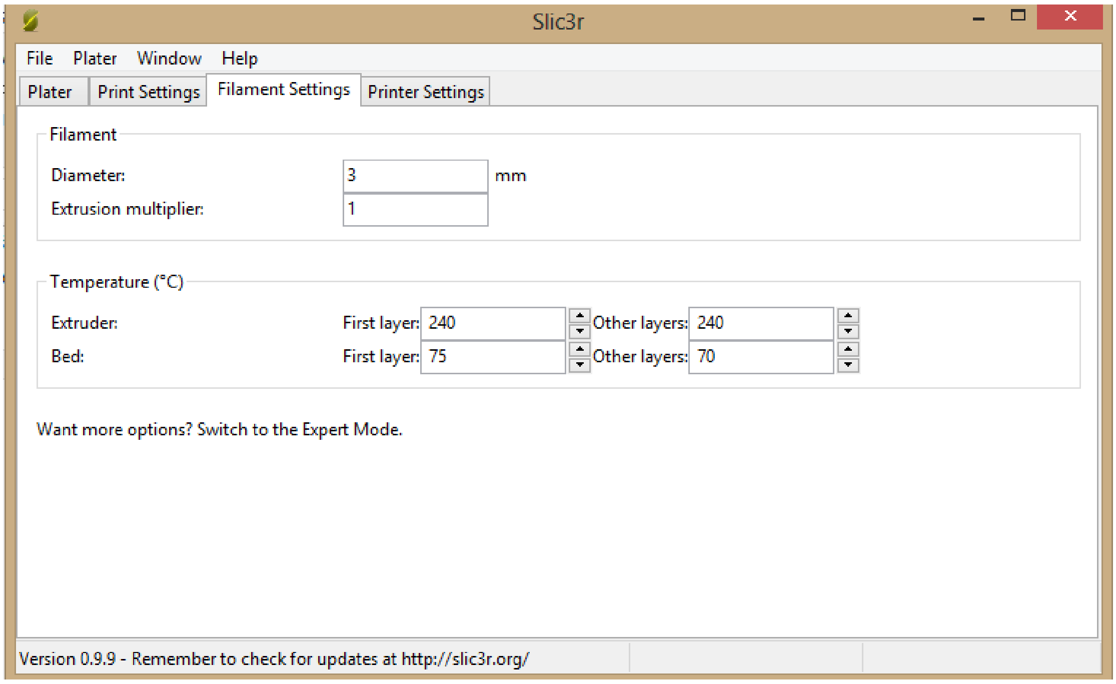

Fig. 26 - 3D model to G-code converter software

Since in the extrusion based 3D printing technology, multiple filament materials are used, the temperature of extruder and bed has to be set according the melting temperature of individual plastic compound used. Temperatures for Heat bed are derived experimentally and depend also on printing surface used.

Table 8 - Temperature settings [RepRap, 2004]

Material	Heat bed temperature [°C]	Extruder temperature [°C]
ABS	110	220-250
PLA (4032D)	90	230
PLA (4042D)	70	190
PLA (4043D)	60	180

4.6 Printing procedure

With proper calibration printer is ready to print. First step is to convert 3D model to list of G-code instructions. This is done by special software, which slices the model to individual layers and sets the path for the printer head. The best freeware software is called Slic3r, which reads STL, AMF and OBJ format files. Once the model is converted to list of G-codes, it is ready to be imported into Pronterface software, by which the printing is carried out. This software is sending G-codes to the printer, which executes them. The time of extrusion is depended on the amount of material needed for creating of desired object. It is important to pre-heat the heat bed and extruder before initiating the print.

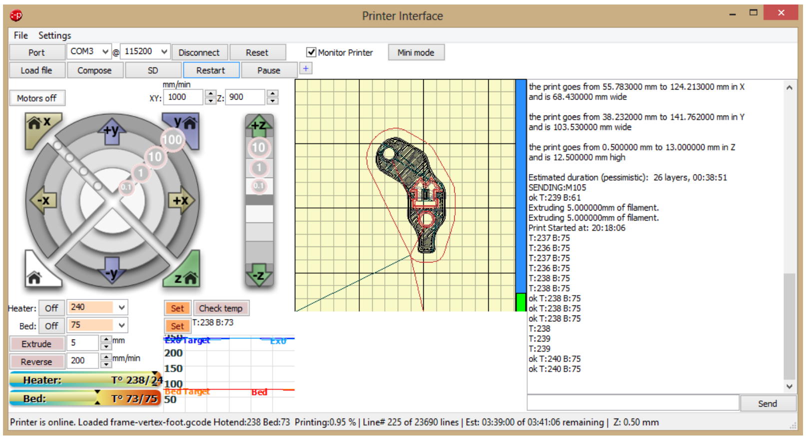

Fig. 27 – Import of G-coded object into Pronterface

Software is automatically checking the outputs from printer to control the temperature. Once the printing command is entered, printing head is relocated to the home position, which is determined by axis endstop microswitches. Software waits until desired temperatures are achieved, before initiating the print. Once everything is hot enough, the print is started automatically.

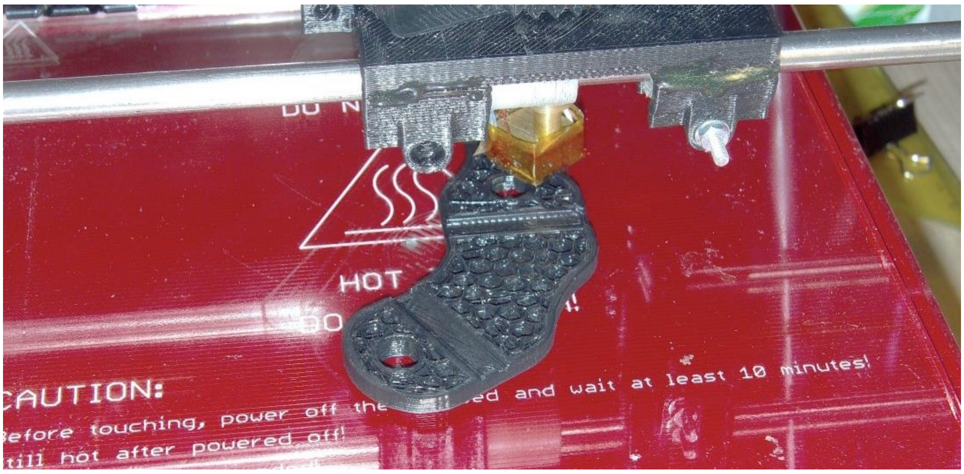

Fig. 28 - The printing process

5. Conclusion

The main task of this thesis was to learn information about 3D printing possibilities and construct a most useful laboratory model of 3D printer. I decided to choose design of RepRap project printer called Prusa-Mendel.

I was able to obtain all essential components and ensure compatibility among them. To ensure the functionality of the model, I had to learn information about all components I used, how they work and how can I adjust them to my issue. I have constructed the whole new 3D printer, based on RepRap project. I have made few adjustments, which have changed features of my printer and especially its cost. Since this project is low-cost focused, I have made considerable amount of components by myself. Various technical machines were needed to use such are lathe, soldering iron, multimeter, grinders, drilling machine etc. so I learned how to operate them.

The output of this thesis is fully operational 3D printer, which can help and support other laboratory tasks. The model is able to print plastic models with 0.5 mm accuracy and by additional adjustments and calibration accuracy could be dropped down to 0.1 mm.

I believe that this model can become another task for a lot of students in future, because the advantage of this printing machine is, that its printing abilities can be enhanced by multiple adjustment and multiple approaches. Over time, this printer could also exceed results of other much more sophisticated and more expensive printing machines.

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Attachments

Table 9 – The list of components

Quantity	Description	Type	Comments
83	M8 nut	Fastener	
93	M8 washer	Fastener	
6	M8×30 mudguard/ fender washers	Fastener	
2	M4×20bolt	Fastener	
2	M4nut	Fastener	
2	M4washer	Fastener	
22	M3×10bolt	Fastener	
16	M3×25bolt	Fastener	
4	M3×40bolt	Fastener	
70	M3washer	Fastener	
40	M3nut	Fastener	Eight optionally locknut / stop nut
2	M3grub screw/ set screw	Fastener	
3	608roller skate/skateboard bearing	Bearings	
4	Ballpoint pen springs	Spring	
6	M8×370mm	Threaded rod	Three per side
4	M8×294mm	Threaded rod	Front/ rear
3	M8×440mm	Threaded rod	Top / bottom
2	M8×210mm	Threaded rod	Z-lead screw
1	M8×50mm	Threaded rod	Or bolt for X idler
2	8mm×420mm	Smooth rod	
2	8mm×406mm	Smooth rod	Y-bar
2	8mm×350mm	Smooth rod	Z-bar
1	225mm×225mm print top plate	Thick Sheet	
1	140mm×225mmprint bottom plate	Thick Sheet	
1	840mm×5mmT5pitch timing belt	Belt	
1	1380mm×5mmT5 pitch timing belt	Belt	
5	NEMA17 bipolar stepper motor	Stepper	
50	Small cable binder/zip tie	Misc.	
1	Wade's Geared Extruder		Or any other compatible extruder
1	Electronics + endstops		RAMPS, Sanguino
3	30mm×10mmOptoflags	Thin Sheet	If using opto endstops
2	8mm ID spring	Spring	If using opto endstops

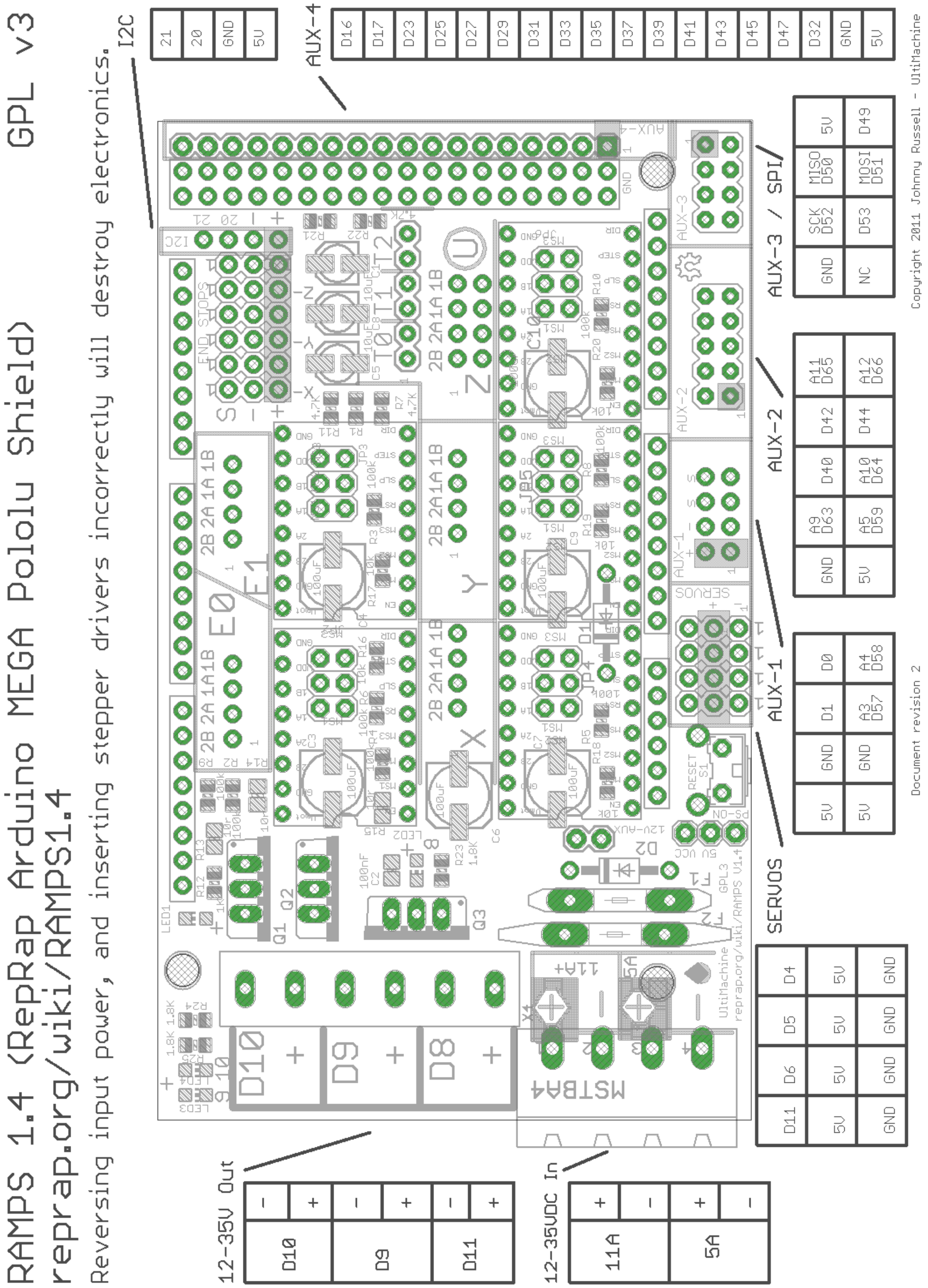

Figure 29 - RAMPS 1.4 connectors [RepRap 2013]

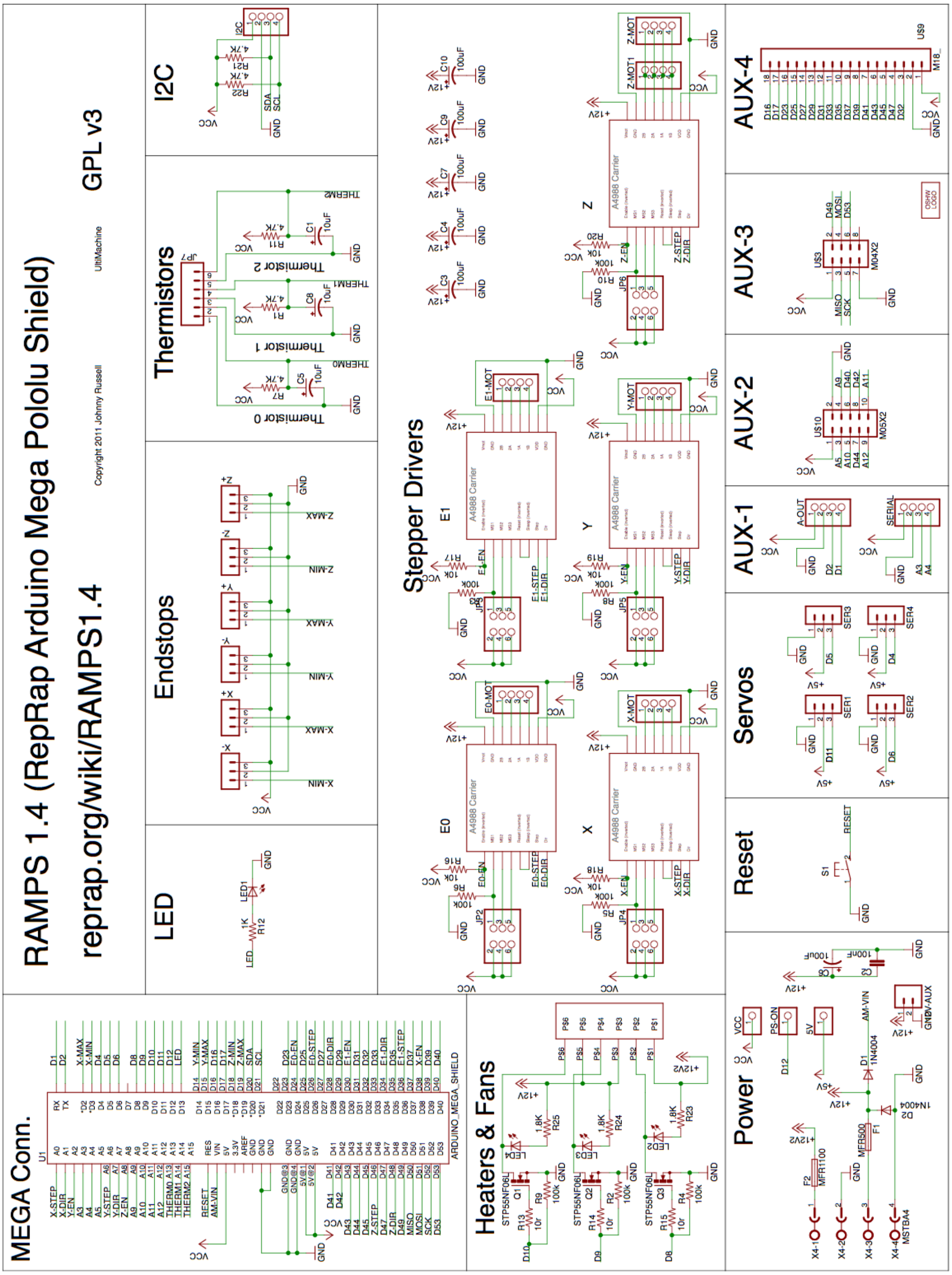

Figure 30 – RAMPS 1.4 schematics [RepRap 2013]